REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB No. 0704-0188

1. AGENCY USE ONLY

2. REPORT DATE
5/22/2001

3. REPORT TYPE AND DATES COVERED
Final Progress Report; 4/15/96 to 11/15/00

4. TITLE AND SUBTITLE
Layering Concept for Wave Shaping and Lateral Distribution of Stresses During Impact

5. Funding Numbers
DAAH04-96-1-0053

6. AUTHOR(S)
J.L. Ding and Y.M. Gupta

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Institute for Shock Physics and Department of Physics
Washington State University
PO Box 642816
Pullman, WA 99164-2816

8. PERFORMING ORGANIZATION REPORT NUMBER
0126681509

9. SPONSORING / MONITORING GENCY NAMES(S) AND ADDRESS(ES)
U.S. Army Research Office
PO Box 12211
Research Triangle Park NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBE
34432-EG
.1

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
The overall objective of this research program was to examine the use of layered targets for distributing dynamic loads in high velocity impacts. Numerical simulations were carried out to address the research objectives. To explore the layering concept, we first used numerical simulations to demonstrate the feasibility of load spreading and wave shaping by layered structures. After the proof of concept, we devised a measure based on normalized dissipative energy density (NDE) to quantitatively characterize load spreading. Using this measure, we were able to gain considerable insight into the mechanisms governing load spreading and the behavior of layered structures to impact. The target properties examined included layering configuration, deformation and fracture behavior of layer materials, and interface properties. Three different approaches were used to treat the interface, namely a thin epoxy later, a slide line, and an interface element governed by irreversible cohesive law. Finally, to correlate load spreading with penetration resistance, we also developed a new energy approach to study the time dependence of the penetration process. The two major contributions from this research program are the demonstration of a potentially useful concept for developing resilient structures to withstand rapid impulsive loading, and the development of a new method to characterize the response of composite targets to such loading.

14. SUBJECT TERMS

20010608 079

15. NUMBER OF PAGES
13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

CLASSIFIED BY:

N/A since Unclassified.

DECLASSIFY ON:

N/A since Unclassified.

Layering Concepts for Wave Shaping and Lateral Distribution of Stresses During Impact (DAAH04-96-1-0053)

Final Progress Report

Submitted to
U.S. Army Research Office

by

J. L. Ding[1] and Y. M. Gupta[2]
Institute for Shock Physics
Washington State University
Pullman, WA 99164-2816

[1] School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164-2920
[2] Department of Physics, Washington State University, Pullman, WA 99164-2814

The main thrust of this research program was to demonstrate the potential of a new approach to enhance the survivability of an armor system. The basic concept is to employ a high wave speed layer to rapidly spread (μs time scales) the impact load in a target or substrate and, thus, reduce the damage imparted to the armor system. In particular, the potential use of thick diamond films for lateral distribution of stresses is an important element of the research effort.

Some inherent challenges associated with the proposed research effort are as follows: How to demonstrate the feasibility of the load spreading concept? How to quantify load spreading? How to compare load spreading for various composite targets in a consistent manner? How to isolate load spreading from other phenomena during penetration? How to correlate load spreading with penetration resistance?

Our approach to address the research objectives was mainly through numerical simulations. The computer codes used included PRONTO and ALEGRA developed by Sandia National Lab., EPIC developed by G. R. Johnson, and DYNA2D developed by Lawrence Livermore Lab. Some preliminary qualitative experiments were also performed. To explore the layering concept, we first used idealized numerical simulations to demonstrate the feasibility of load spreading and wave shaping by layered structures. After the proof of concept, we then devised a measure, based on normalized dissipative energy density (NDE), to quantitatively characterize load spreading. The measure is defined as,

$$NDE = D / E,$$

where D is the dissipative energy per unit initial volume, i.e. $D = (\rho / \rho_0) \int \sigma_{ij} d\varepsilon_{ij}^p$ with $d\varepsilon_{ij}^p$ being the inelastic strain increment, ρ and ρ_0 are the current and initial density respectively, and E is the total energy imparted to the substrate divided by the initial substrate volume. Essentially, this measure is an indication of the degree of localization of dissipative energy in the substrate. The effectiveness of load spreading can be evaluated quantitatively by the distribution of the NDE in the substrate. Using this measure, we were able to gain considerable insight into the mechanisms that govern load spreading and the behavior of layered structures to impact. The target properties examined included deformation and fracture behavior of layer materials, layering configuration, and interface properties. Three different approaches were used to treat interfaces, namely, a thin epoxy layer, a slideline, and an interface element governed by irreversible cohesive law. Finally, to correlate load spreading with penetration resistance, we also developed a new energy approach to study the time dependence of the penetration process.

The convention to identify the various targets discussed in this report is shown in Table 1. Shown in Figure 1 is a demonstration of the load spreading by high wave speed layers. Target (a), i.e. 0S, is made completely of aluminum. Target (b), i.e. 6S, consists of a 20mm thick aluminum substrate and a 6mm thick SiC layer on the top. Target (c), i.e., 2S-2a-2S, has a multilayered configuration in which three 2mm thick layers, namely, SiC-aluminum-SiC, are laid on top of a 20mm substrate. To facilitate a consistent comparison, target (a) should be viewed as composed of 20mm substrate and a 6 mm aluminum (same material as the substrate) layer. It should also be mentioned that load distributions are compared when the shock front reaches some fixed reference points inside the substrate, namely, 1 cm and 2 cm into the substrate. Without layers, target (a) shows a typical quasi-spherical wave diverging from the impact region. With the addition of a high-wave speed SiC layer on the top, the impact stress is spread laterally

as indicated by the stretch of the pressure contour from the top. Target (c) again shows that SiC layer helps spread the load. However because of the low-wave-speed aluminum layer in the middle, the stress distribution becomes more complicated.

Table 1: Definition of layering configurations

Designation	Layer 1	Layer 2	Layer 3	Total Thickness
0S	0.0 mm SiC	6.0 mm aluminum	--	6.0 mm
2S	2.0 mm SiC	4.0 mm aluminum	--	6.0 mm
4S	4.0 mm SiC	2.0 mm aluminum	--	6.0 mm
6S	6.0 mm SiC	0.0 mm aluminum	--	6.0 mm
2S-2a-2S	2.0 mm SiC	2.0 mm aluminum	2.0 mm SiC	6.0 mm
2S-2p-2S	2.0 mm SiC	2.0 mm PMMA	2.0 mm SiC	6.0 mm
2S-2steel(s)-2S	2.0 mm SiC	2.0 mm steel	2.0 mm SiC	6.0 mm
2s-2S-2a	2.0 mm steel	2.0 mm SiC	--	6.0 mm

Figure 2 demonstrates the use of NDE to study the effect of layer properties on load spreading. Specifically, SiC and diamond layers are compared. Both the radial and axial distributions for the SiC have larger gradients and peak values than those for the diamond. A combination of these two distribution yields a simple and clear picture that the dissipative work is more localized in the substrate for SiC than for diamond. Hence, diamond provides a better load spreading capability. Compared to SiC, diamond has higher wave speed, and higher impedance and strength. The better load spreading capability is attributed to all of these properties.

Figure 3 demonstrates the use of NDE to study the effect of layer thickness and layering configuration on load spreading. Comparison of the NDE distributions of 0S, 2S, 4S, and 6S targets demonstrates that load spreading increases with the layer thickness. The figure also shows that multilayered targets that incorporate a soft material in the layering system, function through a combination of shock absorption (gradual and slow load transmission) by the layers and load spreading. Because of the shock absorption by the layers, the impact energy can not be absorbed very quickly by the substrate. Hence the multilayered targets are not as effective as single layered target for load spreading purpose.

Figure 4 shows that layer damage degrades significantly the load distribution capability of the target as demonstrated by the steeper NDE distribution in the damaged targets. Figures 5 and 6 show the imperfect interface also degrades load spreading. The interface was modeled as thin epoxy layer in Figure 5 and a slideline in Figure 6. The initiation and propagation of interfacial crack as modeled by an interface element and a cohesive law is shown in Figure 7.

Figure 8 shows the time dependence of the penetration process as indicated by various energy histories. The dissipative energy in the projectile and the layer energy fraction (the ratio of the energy in the layer to the total energy imparted to the target) are used here as examples. Note that both the projectile defeat capability, as indicated by the dissipative energy in the projectile, and load spreading capability, as indicated by the initial slope of the layer energy history, increase with the layer thickness. Also, layer fracture leads to degraded projectile defeat and load spreading.

Significant results obtained from the current research effort are as follows:

(1) Effective load spreading requires high stiffness or high wave speed to spread the load faster, and high impedance and strength to transmit the load from the layer to the substrate effectively.
(2) The strength of the layer system is the dominant factor for defeating the projectile and reducing the transient time of the penetration event.
(3) Under ideal condition, i.e. no layer fracture or imperfect bonding, a single thick high wave speed layered target offers the best penetration resistance for several reasons. The high strength of the layer allows more impact energy to be converted to the dissipative energy of the projectile, and less to be absorbed by the target. The high stiffness of the layer allows the energy absorbed by the target to be transferred from the layer to the substrate quickly. Furthermore, the high stiffness of the layer allows the impact load and energy transmitted to the substrate to be spread more widely and thus minimize the localized damage in the substrate.
(4) A multilayered target with a relatively soft layer sandwiched between two hard layers offers less penetration resistance than a single thick hard layer because the soft layer reduces both the strength and stiffness of the layer system.
(5) Layer damage degrades significantly the capability of the target to defeat the projectile and spread the load.
(6) Imperfect interface appears to play limited role on projectile defeat and transient time of the penetration event. Its major effect appears to be a more localized distribution of impact load and energy.
(7) Since load spreading enhances the integrity of the target, it is also expected to enhance the penetration resistance because the projectile can penetrate only if it can move away the target material ahead of it. However, the extent of the contribution of load spreading to overall penetration resistance is still not clear at this point.
(8) The single or multiple initiation of interface cracks occurs in shear or pure mode II loading irrespective of the interface depth from the impact surface and the material on either side. The initiation speed of interface cracks is more than the longitudinal wave speed of the materials. However, the crack speed reduces quickly and falls below the shear wave speed of the more compliant material. The subsequent crack propagation depends on the shape of the traveling stress wave, target material response to wave loading, interface properties, and friction.

List of Publications

(a) Papers published in non-peer-reviewed journals or in conference proceedings.

Gupta, Y. M., Ding, J. L. and Robbins, J. R., 1999, "Wave shaping and lateral spreading of impact load using layered materials and structures," *Proc. of the 15th US Army Symposium On Solid Mechanics*, April 1999, Myrtle Beach, South Carolina.

(b) Manuscripts submitted, but not published

Gupta, Y. M. and Ding, J. L., Impact load spreading in layered materials and structures: concept and quantitative measure, *submitted to Int. J. of Impact Engrg.*

(c) Manuscripts to be submitted.

Robbins, J. R., Ding, J. L., and Gupta, Y. M., Numerical investigation of load spreading and penetration resistance of layered structures

Dwivedi, S. K., Ding, J. L., and Gupta, Y. M., Effect of interface failure on load spreading in multilayered targets.

Dwivedi, S. K., Ding, J. L., and Gupta, Y. M., Effect of projectile shape and velocity on load spreading in multilayered targets.

(d) Thesis

"Numerical investigation of load spreading and penetration resistance of layered structures" by J. R. Robbins (1999). Now employed at Sandia National Laboratories.

(e) Technical reports submitted to ARO

1997 Interim Progress Report
1998 Interim Progress Report
1999 Interim Progress Report

Scientific Personnel Supported

Mr. Josh Robbins, Graduate Student
Dr. Sunil Dwivedi, Research Associate
Dr. J. L. Ding, Professor
Dr. Y.M. Gupta, Professor

Inventions

None

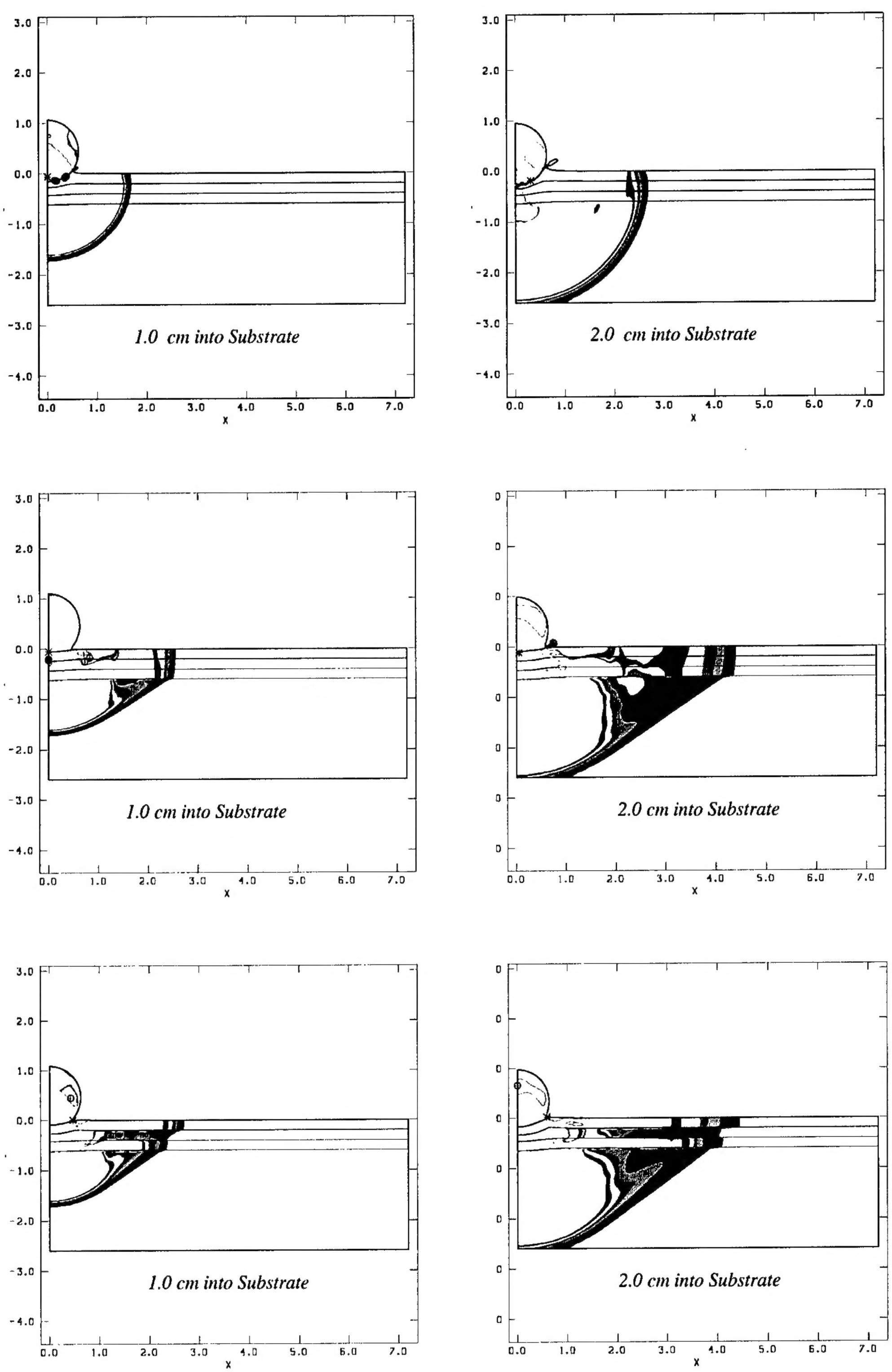
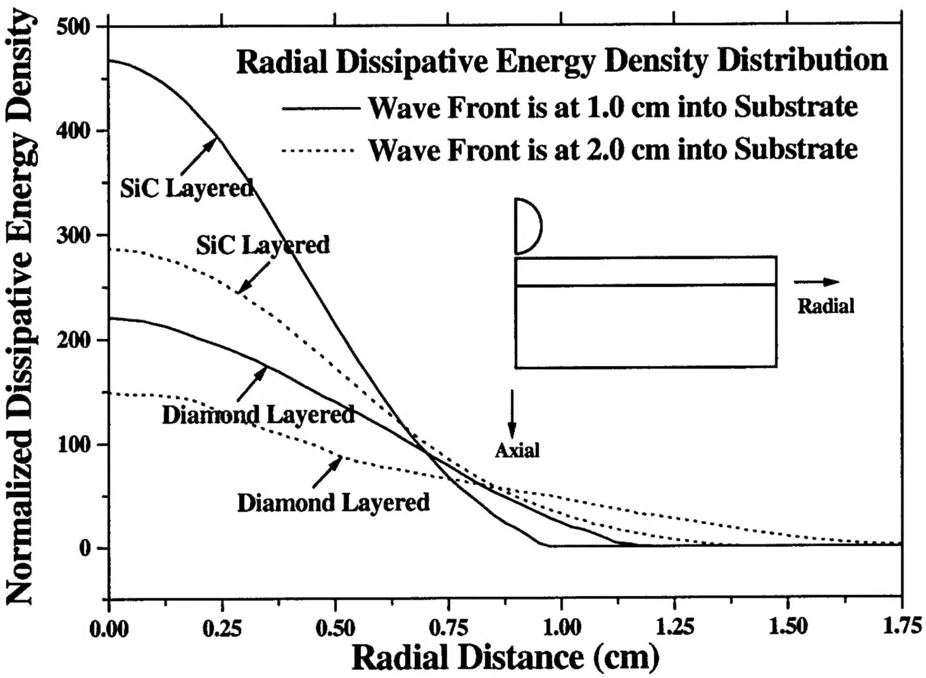


Figure 1: Numerical demonstration of load spreading by a SiC layer. Target (a) is made completely of aluminum, target (b) has a 6 mm SiC layer, and target (c) has three 2 mm thick layers, SiC-aluminum-SiC, above the substrate. The total thickness of all the targets is 26 mm.



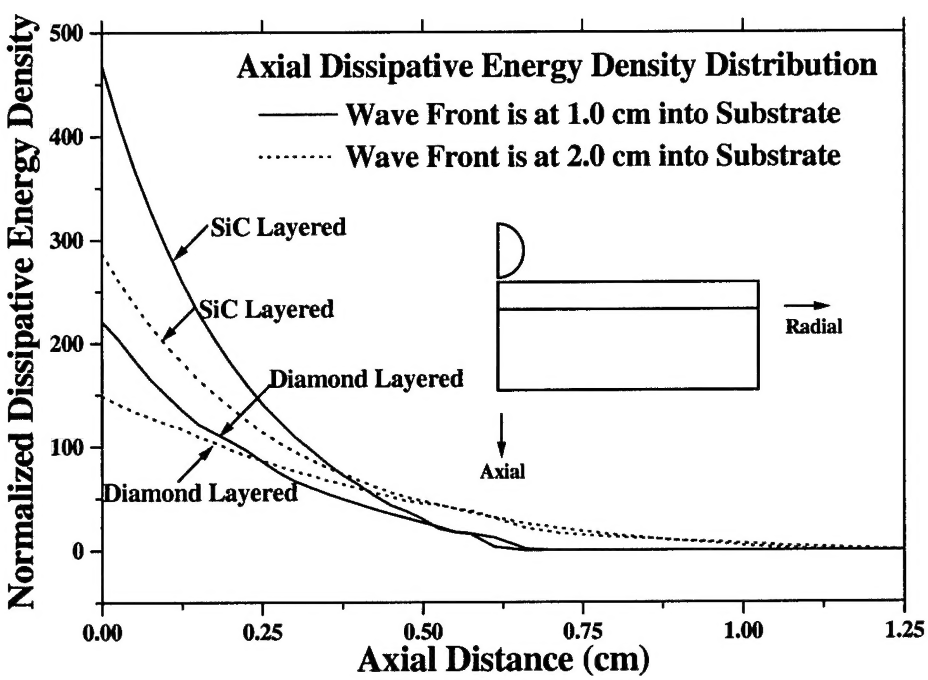


Figure 2: NDE distribution for an aluminum substrate in response to two different layering materials (2mm thick), SiC vs. diamond.

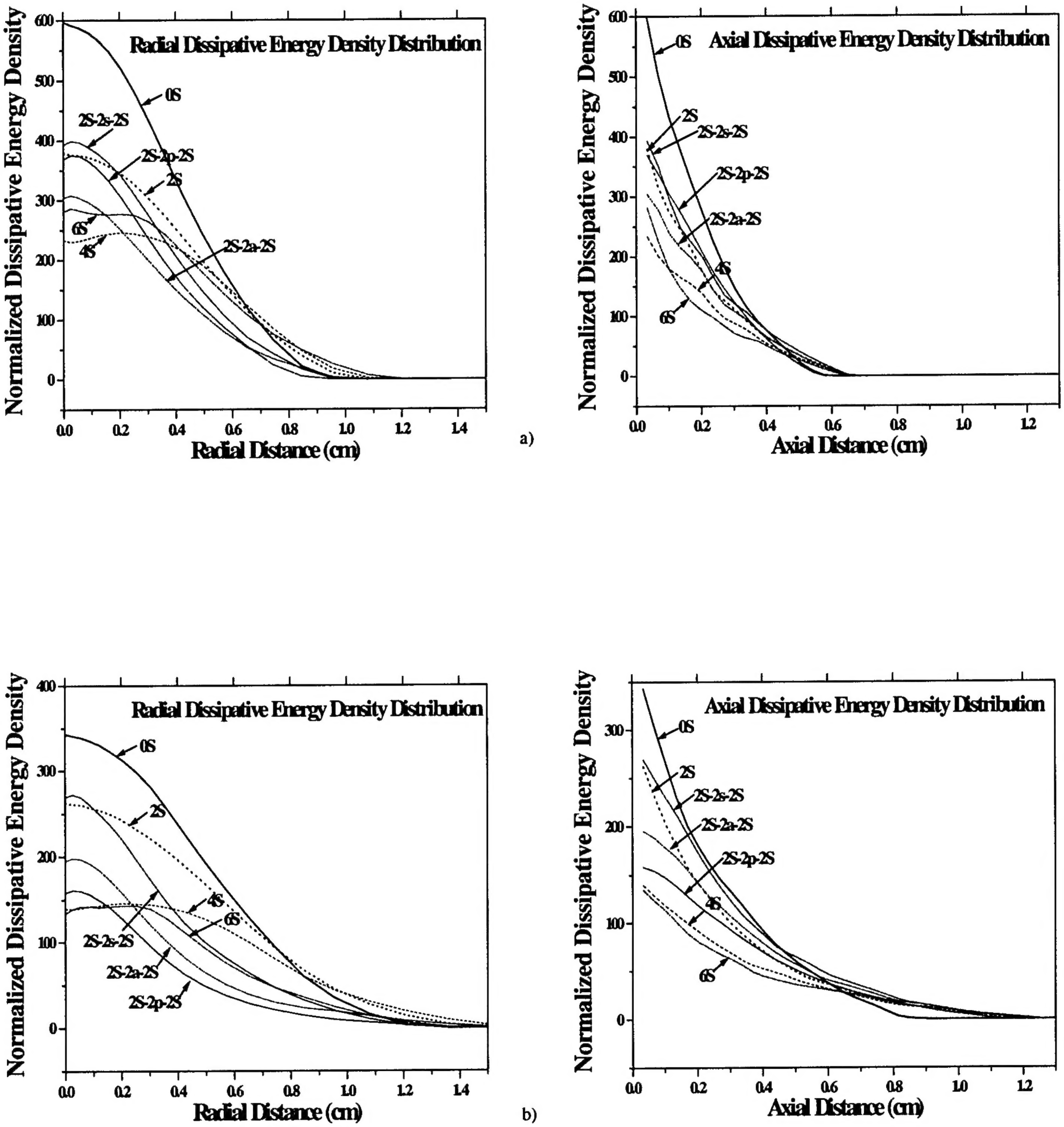
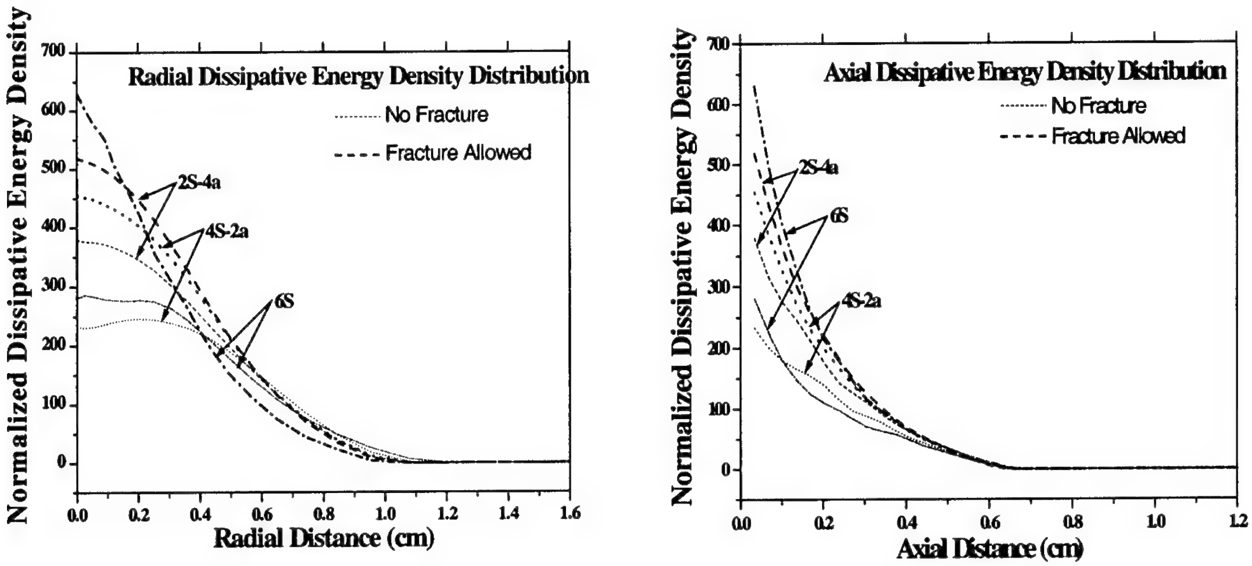
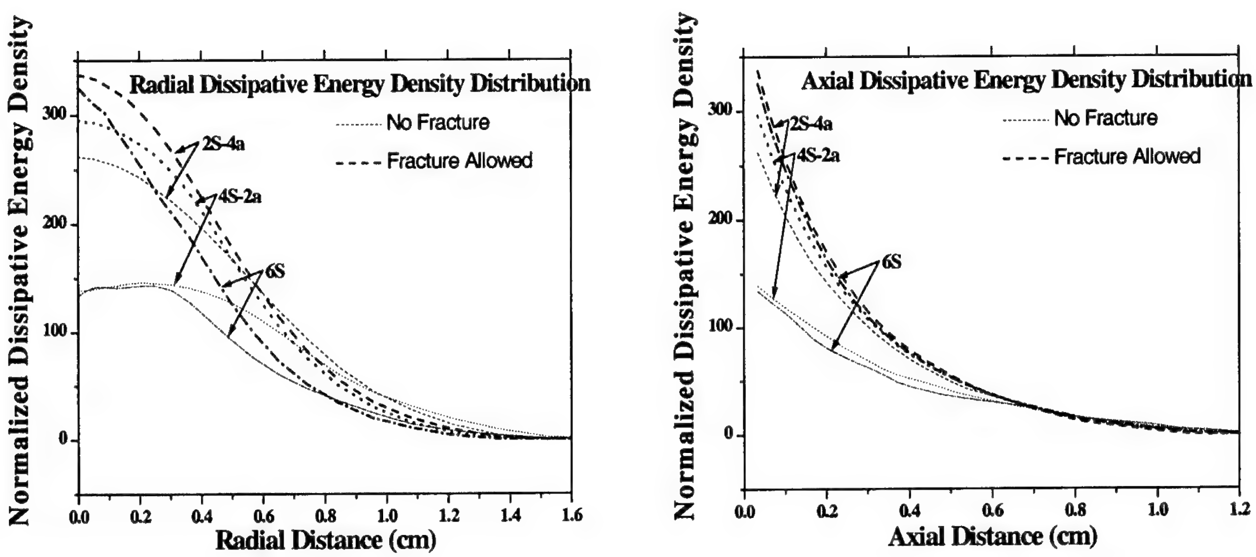


Figure 3: Radial and axial distribution of normalized dissipative energy density in an aluminum substrate for various SiC layering configurations. The damage of SiC is suppressed. The shock front is at, (a) 1 cm, and (b) 2 cm, into the substrate.

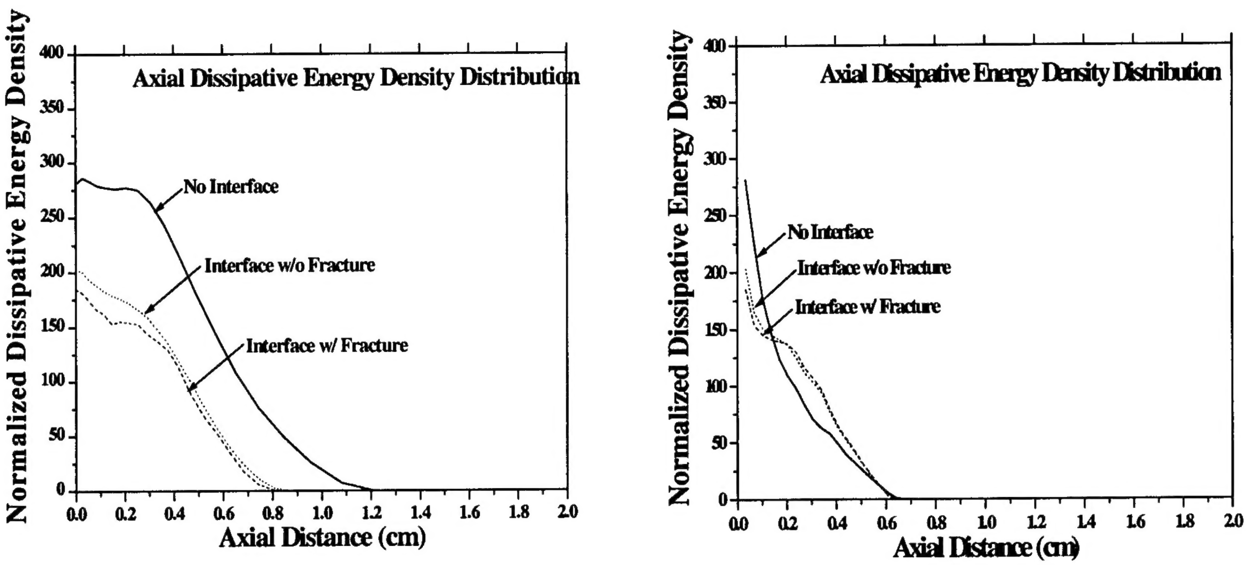


(a)

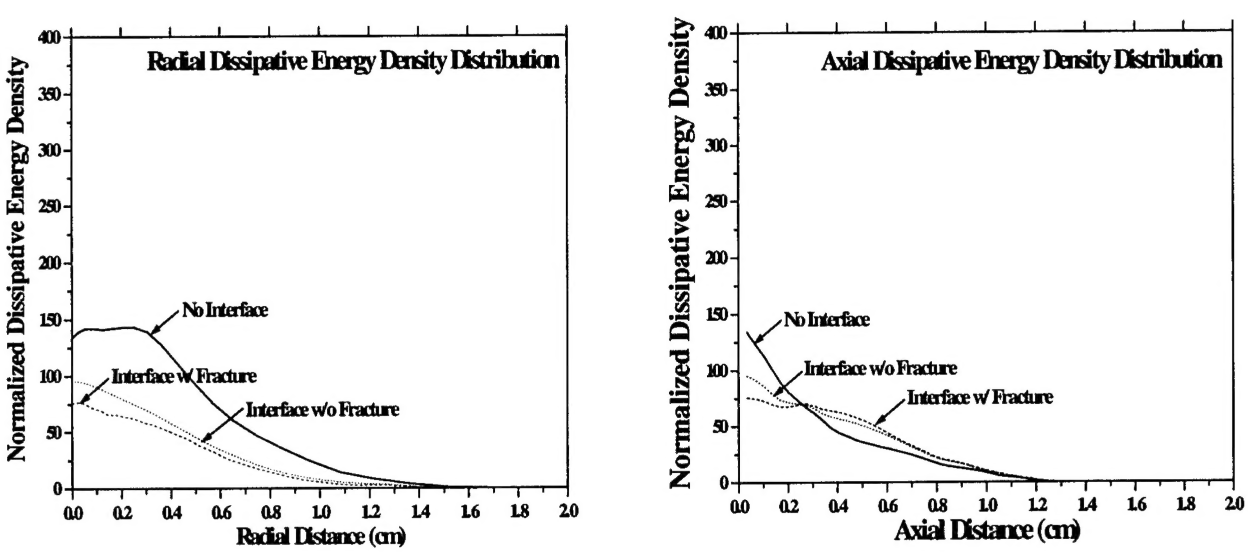


(b)

Figure 4: Effect of layer damage on NDE distributions for single-layered targets. The shock front is at, (a) 1 cm, and (b) 2 cm, into the substrate.

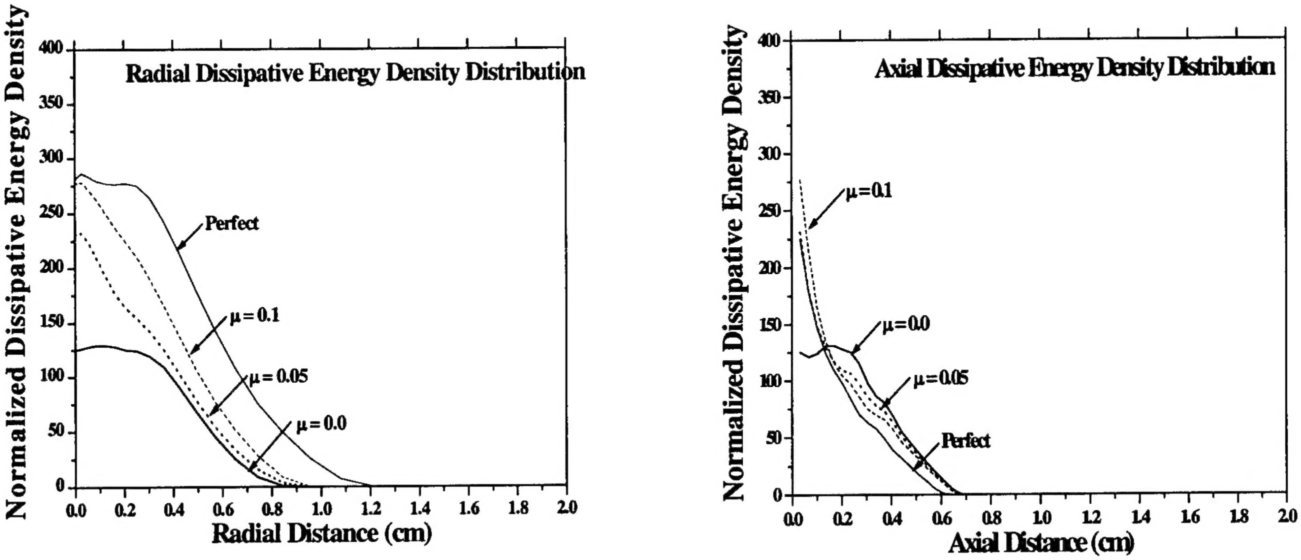


(a)

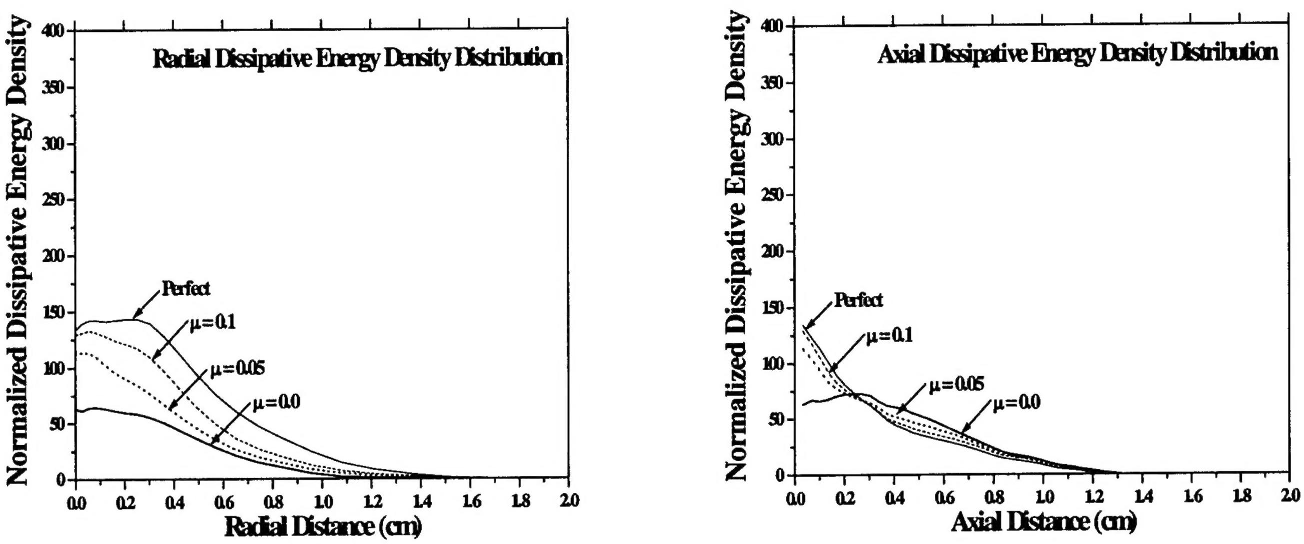


(b)

Figure 5: NDE distributions for 6S target with and without epoxy bond between layer and substrate. The shock front is at, (a) 1 cm, and (b) 2 cm, into the substrate.



(a)



(b)

Figure 6: Effect of frictional coefficient on NDE distributions for the 6S target when the interface between the layer and the substrate is treated as slideline. The shock front is at, (a) 1 cm, and (b) 2 cm, into the substrate.

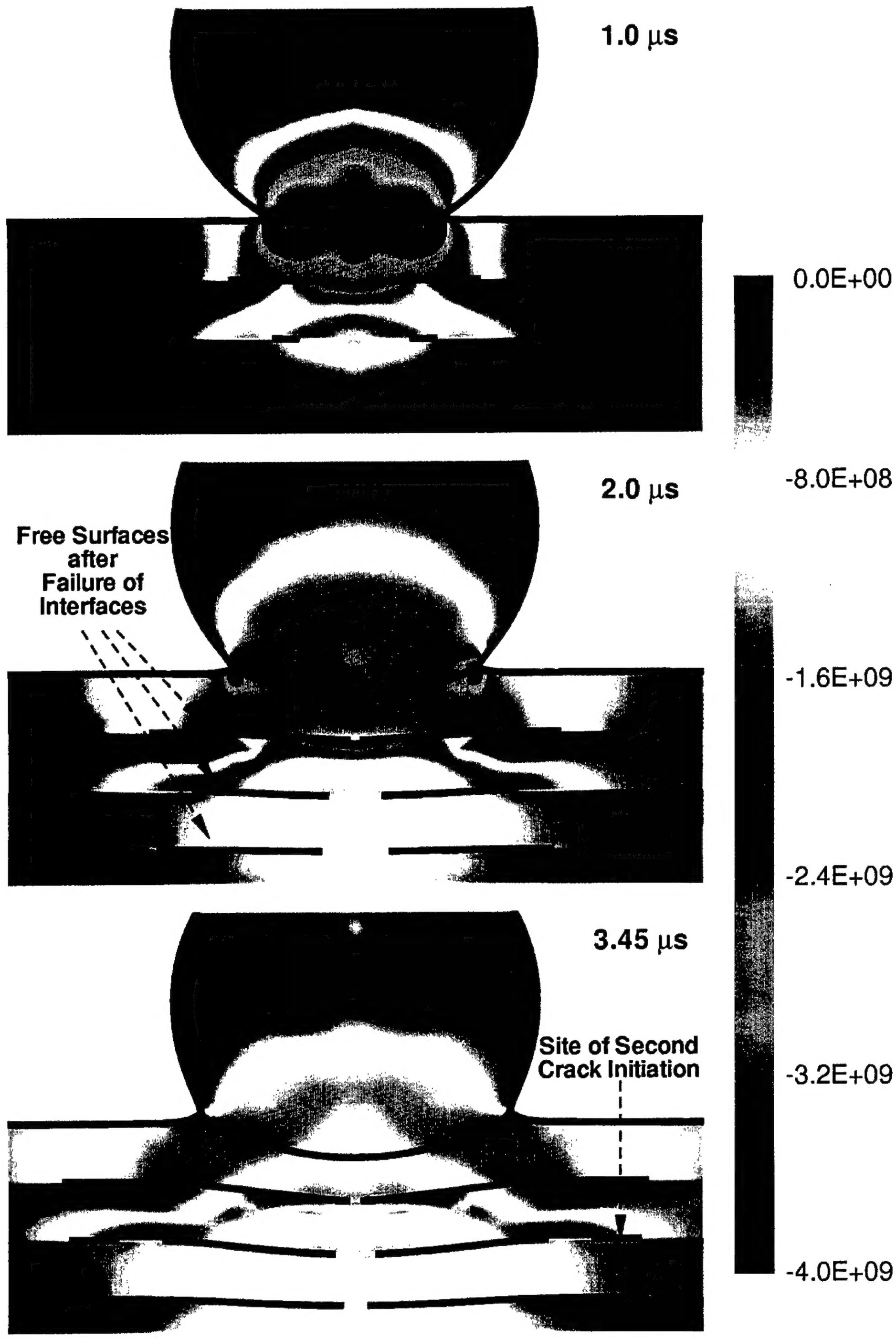


Fig. 7: Contours for the radial stress at three time instances showing the pre-cursor wave in the SiC layer that initiates the second crack at S-a interface in the 2s-2S-2a target.

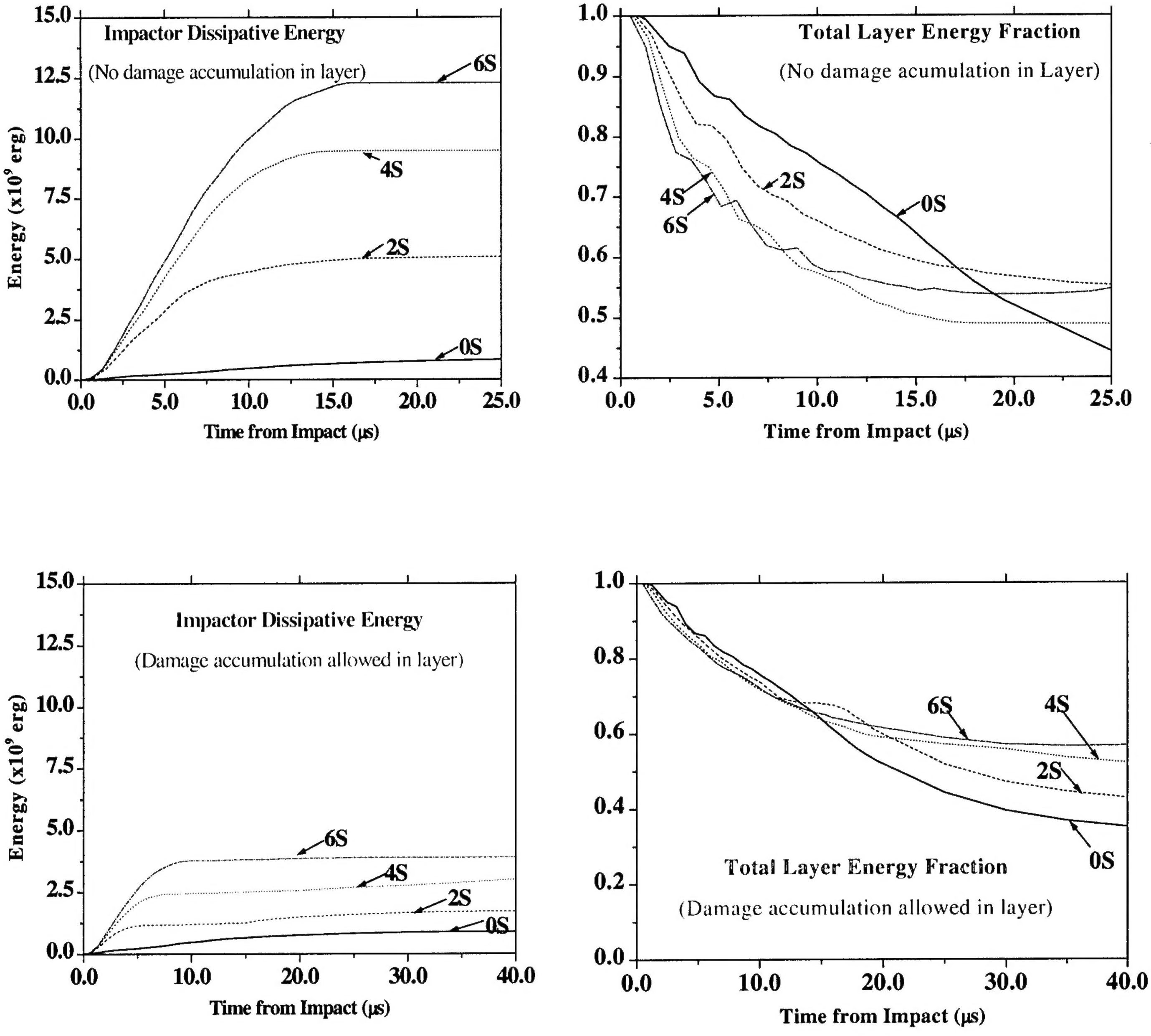


Figure 8: The time dependence of the penetration process as indicated by various energy histories.